EWK Physics at the Tevatron

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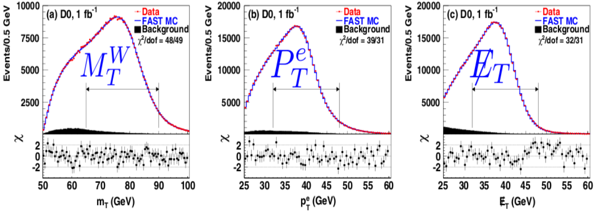
Outline

- W, Z properties
  - Wmass at DØ
  - Wmass at CDF $\rightarrow$ see talk by Bodhitha Jayatilaka
  - $Z\gamma * \Delta\sigma/\Delta p_T$
- V+γ physics
  1. Wγ
  2. Zγ
- Massive Diboson Physics
  1. WZ
  2. ZZ



80.401 ± 0.023 (stat.) ± 0.037 (syst.) GeV

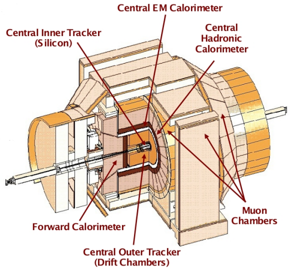
80.400 ± 0.027 (stat.) ± 0.040 (syst.) GeV

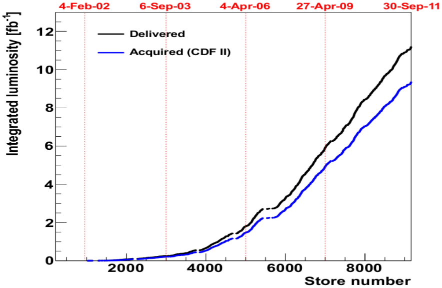
80.402 ± 0.023 (stat.) ± 0.043 (syst.) GeV

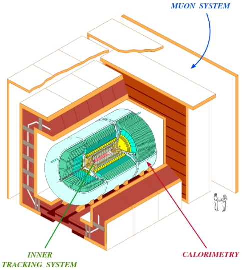
$$\mathrm{M_W} = 80.401 \pm 0.021(stat.) \pm 0.038(syst.)\ \mathrm{GeV}$$
$$= 80.401 \pm 0.043\ \mathrm{GeV}$$

The CDF and DØ experiment

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96\ TeV$
- 36 bunches, 392 ns
- record peak luminosity: $4.1 \cdot 10^{32} cm^{-2} s^{-1}$
- CDF and DØ: multipurpose detector
- more than 12 fb^{-1} delivered and $\sim$ 10 fb^{-1} acquired

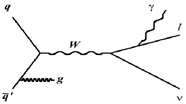


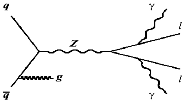




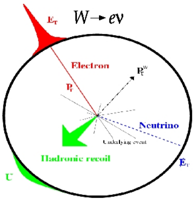
W/Z production at the Tevatron

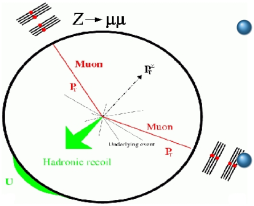
- Dominant production mechanism: $q\bar{q}'$ annihilation





- At Tevatron W and Z hadronic decays are overwhelmed by QCD background
- Identification through leptonic decays

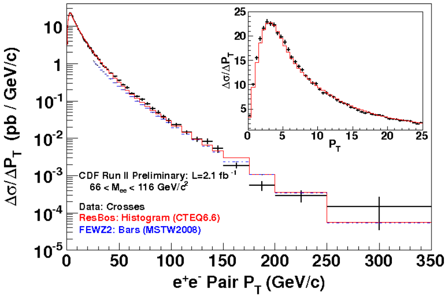


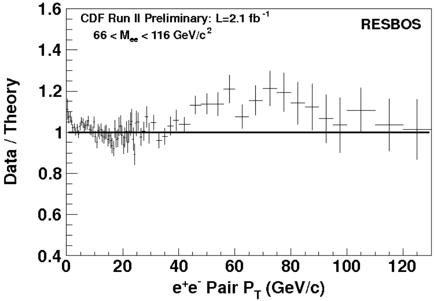


- Electrons:
  - good EM shower shape
  - small hadronic energy
  - isolated in calorimeter
  - well-matching good track
- Muons:
  - MIP in calorimeter
  - isolated hits in muon chamber
  - well-matching good track
- Z selection:
  - 2 oppositely charged electrons or muons invariant mass consistent with m_Z
- W selection:
  - exactly one lepton
  - energy imbalance in event $\not{E}_T$

$Z\gamma * \Delta\sigma / \Delta p_T$

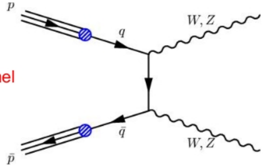
- Select Z boson pairs using pair of electrons in the whole eta range of the detector and $66 < M_{ll} < 116$ GeV/c^2
- Pythia 6.2 simulation of $pp \to \gamma * /\bar{Z} \to ee + X$ +Photos 2.0 for final QED radiation
- The simulated, reconstructed event p_T distribution that pass all analysis cuts disagrees with the data, so the underlying Pythia p_T is tuned.
- The simulation's calorimetric energy scales and resolutions are tuned to the data using dielectron mass and electron E_T distributions



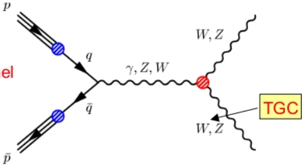


Diboson: Finding rare processes

t-channel



s-channel



s-channel sensitive to Triple Gauge Couplings:

Charged TGC
- $q\bar{q}' \to W^* \to W\gamma : WW\gamma$
- $q\bar{q}' \to W^* \to WZ : WWZ$
- $q\bar{q} \to Z/\gamma^* \to WW : WW\gamma, WWZ$

Charged final states only possible at hadron colliders!

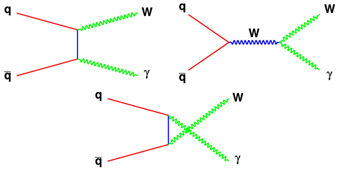
Neutral TGC
- $q\bar{q} \to Z/\gamma^* \to Z\gamma : \boxed{Z\gamma\gamma, ZZ\gamma}$
- $q\bar{q} \to Z/\gamma^* \to ZZ : \boxed{Zz\gamma, ZZZ}$

absent in SM!

- Di-bosons are reality check on path to finding multilepton final states with very small $\sigma * BR$
- Significant backgrounds for several interesting processes
- Trilinear Gauge Coupling (TGC) measurements
  1. s-channel is susceptible to anomalous triple gauge couplings: K^z,K^γ,g_1^z,g_1^γ,λ^z,λ^γ
  2. TeV with respect to LEP: explores higher energy range
  3. To ensure cross sections do not violate unitarity, a form factor is introduced $\Delta a(\hat{s}) = \Delta a_0/(1 + \hat{s}/\Lambda^2)^n$

$W\gamma$ (4.2 fb^{-1}): DØ

- Interesting for its sensitivity to BSM signatures
- **Interference between tree level amplitudes produces a zero amplitude at a specific angle $\theta*$ between the W and the incoming q**
- The radiation amplitude zero is visible in the $Q \times (\eta_{mu} - \eta_{\gamma})$ as a dip at -0.3
- Events with $W \to \mu\nu + \gamma$:
  - Muon $p_T >$ 20 GeV/c , Electron $E_T > 25GeV$ $\not{E}_T >$ 20 GeV
  - $E_T(\gamma) >$ 15 GeV
  - $\Delta R(\mu\gamma)$ >0.7,



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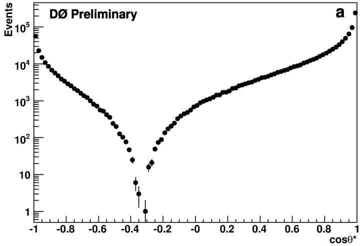
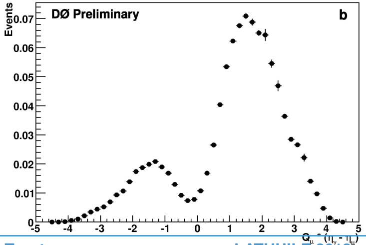
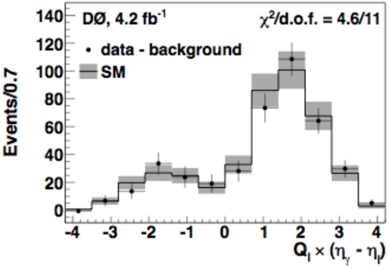


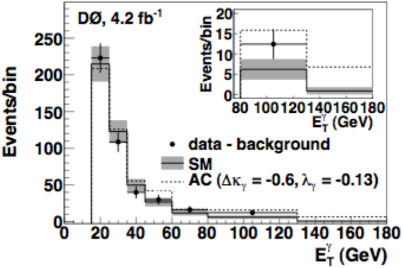


- The charge signed photon-muon rapidity difference background subtracted data agrees with the SM.
- Proceed to set upper limits on $WW\gamma$ couplings using the γ E_T distribution
- More details in http://arxiv.org/abs/1109.4432v2 Phys. Rev. Lett. 107, 241803 (2011)

$p\bar{p} \to W\gamma$ = 7.6 $\pm$ 0.4 (stat.) $\pm$ 1.6 (syst.) pb (SM= 7.6 $\pm$ 0.2 pb)

$-0.4 < \Delta\kappa_\gamma < 0.4$ and $-0.08 < \lambda_\gamma < 0.07$ for $\Lambda =$ 2.0 TeV at 95 % CL.





$W\gamma$: results

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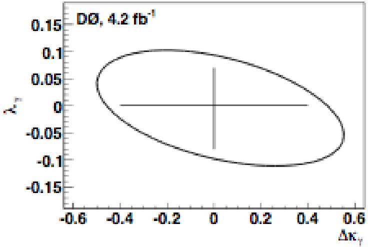
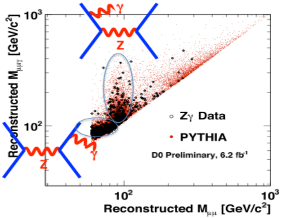
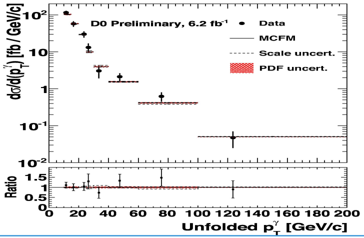


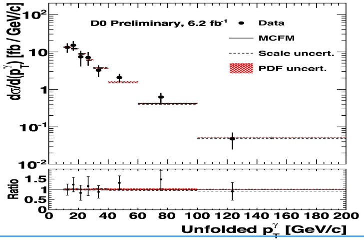
$Z \rightarrow \mu\mu + \gamma(6.2\, fb^{-1}) : D\emptyset$

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/EW/E37/

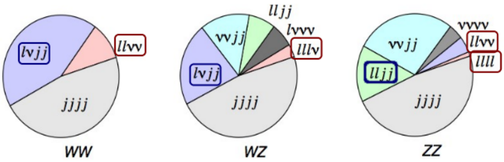


- Select 1000 events of $Z \rightarrow \mu\mu + \gamma$:
  1. 2 hight p_T muons with $M_{ll} > 60 GeV/c^2$
  2. Reconstructed photon with $p_T >$ 10 GeV/c and $\Delta R(mu, \gamma) > 0.7$
- $\boldsymbol{\sigma = 0.31 \pm 0.03(stat.) \pm 0.02(syst.)\ (SM = 0.29 \pm 0.01)pb}$
- Differential cross section obtained with invert matrix for two samples
  - $M_{ll\gamma} > 0$ GeV/c^2
  - $M_{ll\gamma} > 100$ GeV/c^2 to reduce FSR contribution (308 events)





Heavy Diboson Production

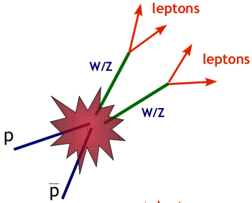


Leptonic Decay Channels

Small branching fraction and low background

Clean signal but low yields

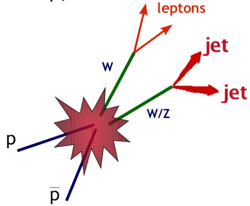
Key $\rightarrow$ increase lepton acceptance



Semileptonic Decay Channels

Larger branching fraction and much larger backgrounds

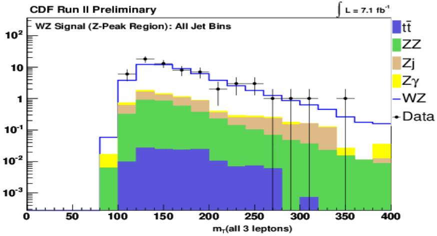
Signal / Background $< 0.5\%$

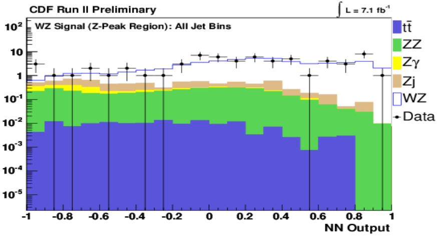


WZ$\rightarrow \ell\ell\ell\nu$: CDF

- Event selection:
  - Exactly three leptons (1st with $p_T > 20$ GeV and 2nd, 3rd with $p_T > 10$ GeV), $\not{E}_T > 25 GeV$
  - Z-selection, a pair of same flavor, opposite charge leptons with $76 < m_{ll} < 106$ GeV
  - ZZ biggest background $\rightarrow$ Trilepton + track rejection to remove events with a 2nd Z-boson.
- A neural network to separate S from B $\rightarrow$ Templates are fitted to data using a binned maximum likelihood fit.

$$\sigma(WZ) = 3.9^{+0.6}_{-0.5}(stat.)^{+0.6}_{-0.4}(syst)pb\ (SM\ = 3.46 \pm 0.21pb)$$





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- Extract from Z p_T distribution also TGC limits $\rightarrow$ HISZ scheme= 3 parameters

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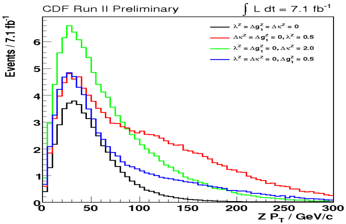

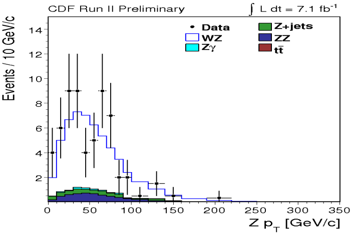

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- Public Web Page Link 1, Link 2

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CDF Results at 7.1fb^{-1}

	λ^Z	Δg_1^Z	$\Delta\kappa^Z$
1.5TeV	-0.08 - 0.10	-0.09 - 0.22	-0.42 - 0.99
2.0TeV	-0.09 - 0.11	-0.08 - 0.20	-0.39 - 0.90

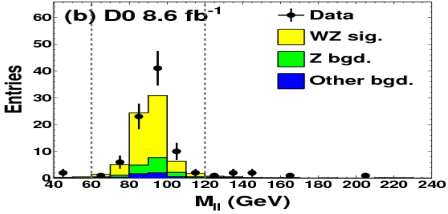
CDF Expected Limits at 7.1fb^{-1}

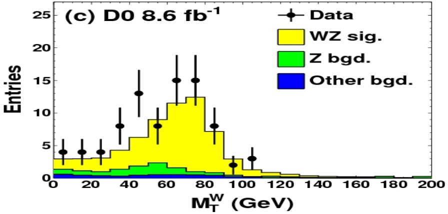
	λ^Z	Δg_1^Z	$\Delta\kappa^Z$
2.0TeV	-0.10 - 0.10	-0.11 - 0.20	-0.53 - 0.86
1.5TeV	-0.11 - 0.12	-0.12 - 0.23	-0.58 - 0.94

$WZ \rightarrow \ell\ell\ell\nu$: DØ

- Do not restrict the offline event selection to events satisfying specific trigger conditions $\rightarrow$ analyse all recorded data in order to maximise the event yields
- Event selection:
  - Exactly three leptons: 1st with $p_T > 20$ (15) GeV and 2nd, 3rd with $p_T > 15$ (10) GeV
  - Z-selection, a pair of same flavour, opposite charge leptons with $60 < m_{ll} < 120$ GeV
- Likelihood fit to the M_T to extract cross section
- Total cross section uncertainty reduced by taking the ratio to $Z \rightarrow \ell\ell$ and then multiplying to theory

$$\sigma(WZ) = 4.50 \pm 0.61(stat.)^{+0.16}_{-0.25}(syst.)\ pb\ (SM\ = 3.46 \pm 0.21)pb$$

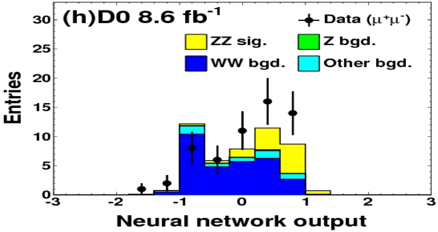


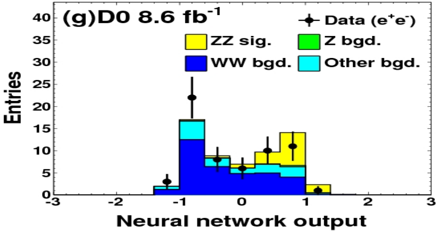


$ZZ \to \ell\ell\ell\ell$: DØ

- Measure at the same time also ZZ cross section
- Same selection as before but requiring 4 leptons
- Fit to the NN distribution to extract cross section
- Total cross section uncertainty reduced by taking the ratio to $Z \to \ell\ell$ and then multiplying to theory
- http://arxiv.org/abs/1201.5652

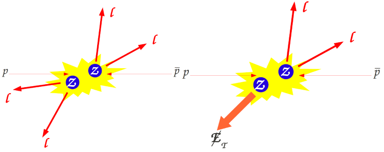
$$\sigma(ZZ) = 1.64 \pm 0.44(stat.)^{+0.13}_{-0.15}(syst.)\ pb\ (SM = 1.30 \pm 0.10\ pb)$$



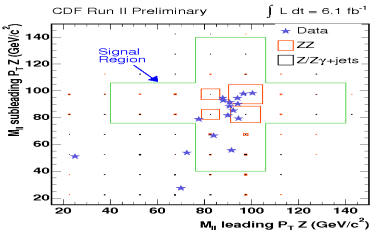


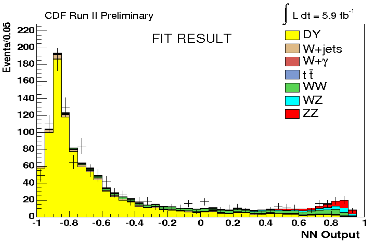
$ZZ \to \ell\ell\ell\ell$ and $ZZ \to \ell\ell\nu\nu$

- Combination of two measurements:
  - ZZ $\to \ell\ell\ell\ell \to$ Small BR, low background
    - Counting experiment $\sigma(ZZ) = 2.03^{+0.62}_{-0.54}(stat.) \pm 0.27(syst.)\ pb$
  - ZZ $\to \ell\ell\nu\nu \to$ Larger BR, large Drell-Yan background. More precise measurement.
    - Use a NN to extract the cross section $\sigma(ZZ) = 1.34^{+0.42}_{-0.39}(stat)^{+0.38}_{-0.28}(syst)\ pb$



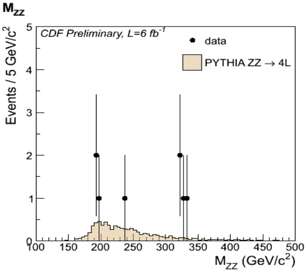
- Combination is $\sigma(ZZ) = 1.64^{+0.44}_{-0.38}\ pb$
- http://arxiv.org/abs/1112.2978





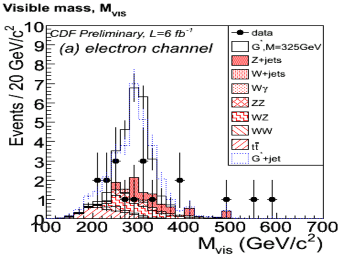
ZZ high mass resonance search CDF

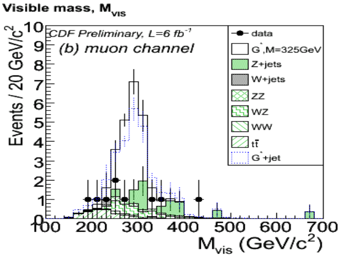
- ZZ production is sensitive to new physics, for example a Higgs boson or a Randall-Sundrum (RS) graviton decaying to two Z bosons
- Explore 3 channels:
  - 4 leptons; 2 with $p_T > 20$ GeV: two same flavor pairs with invariant mass in $76 - 106$ GeV
    - **4 events are consistent with $M_{ZZ} = 325$ GeV/c^2 !**



ZZ high mass resonance search CDF

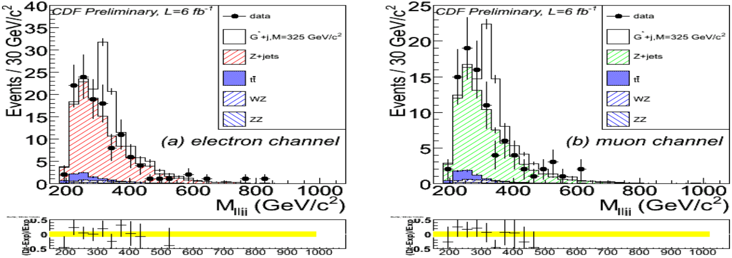
- ZZ production is sensitive to new physics, for example a Higgs boson or a Randall-Sundrum (RS) graviton decaying to two Z bosons
- Explore 3 channels:
  - 2 leptons + $\not\!\!E_T$: $\not\!\!E_T > 100$ GeV, one reconstructed Z boson





ZZ high mass resonance search CDF

- ZZ production is sensitive to new physics, for example a Higgs boson or a Randall-Sundrum (RS) graviton decaying to two Z bosons
- Explore 3 channels:
  - 2 leptons + 2 jets: jet $p_T > 25$ GeV; with the jet pair invariant mass in $70 - 100$ GeV



ZZ high mass resonance search CDF

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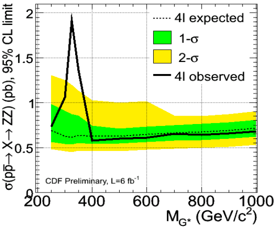
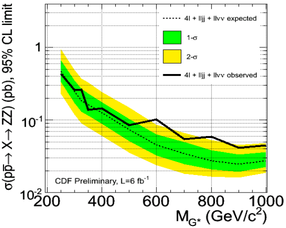
- Explore 3 channels:

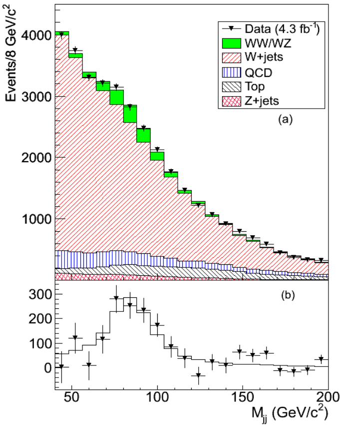
- Reinterpret the results in the terms of graviton models → **Phys. Rev. D85 012008 (2012)**

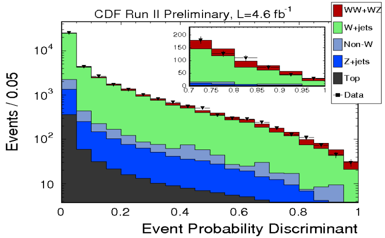




$WW/WZ \to \ell\nu jj$: CDF

- Semileptonic final states have larger BR and much larger backgrounds. Two analysis:
  - First approach uses the shape of Mjj to look for a clear resonance (Phys.Rev.Lett.104:101801,2010)
  - Second approach uses a matrix element calculation to build discriminant (EPD) to separate S and B (Phys. Rev. D 82, 112001 (2010))

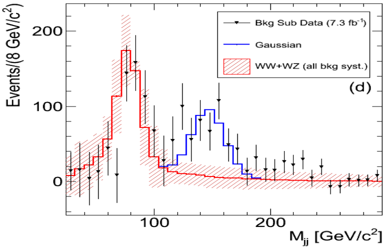




$$\sigma(WW/WZ) = 18.1 \pm 3.3(stat) \pm 2.5(syst)\ pb$$

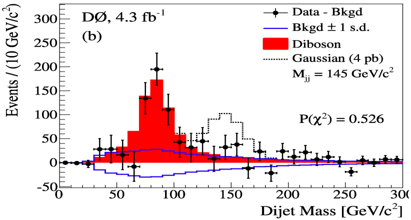
$$\sigma(WW/WZ) = 16.5^{+3.3}_{-3.0}(stat + syst)\ pb$$

Wjj anomalous production



- **4.1σ excess seen in dijet mass spectrum of W+2jet sample**
  - Binned χ^2 fit to Mjj distribution consistent with $\sigma = 3.0pb \pm 0.7$
  - Many cross checks performed: various bkg control regions, W+jets modelling etc
- PHYS. REV. LETT. 106, 171801 (2011), and Public Webpage

- DØ repeated CDF analysis $\rightarrow$ with some minor differences
- **No significant discrepancy w.r.t. background model**
- Results are 2.5 σ apart
- Phys.Rev.Lett. 107 (2011) 011804

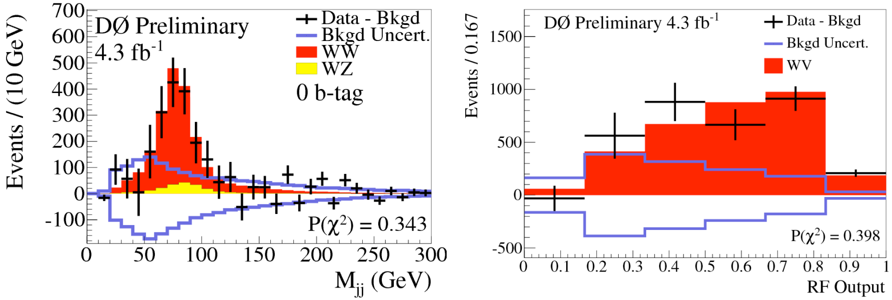


- **S/B 10x worse at LHC**
- **Hard to understand $W+$ jets at that level**

- One single reconstructed lepton + $\not\!\!E_T$ + 2 jets with $p_T > 20$ GeV
- Signal and background are separated using a Random Forest classifier
- Cross section is extracted with a likelihood fit to the RF output

$$\sigma(WW/WZ) = 19.6^{+3.2}_{-3.0}\ (SM = 15.9 \pm 0.1pb)$$

- Observed significance 7.9σ (5.9 expected) → http://arxiv.org/abs/1112.0536v1



$WW/WZ \to \ell\nu jj$: DØ

- One single reconstructed lepton + $\not{E}_T$ + 2 jets with $p_T > 20$ GeV
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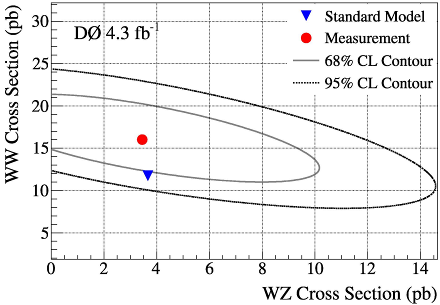
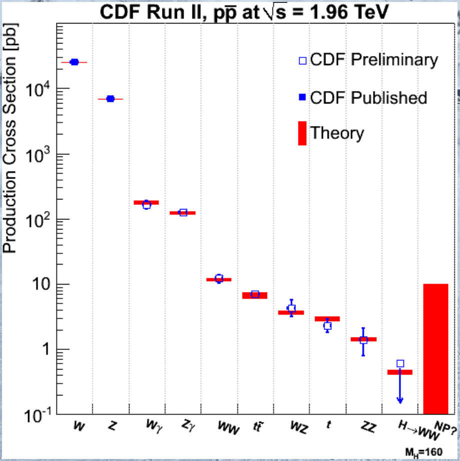
$$\sigma(WW/WZ) = 19.6^{+3.2}_{-3.0}\ (SM = 15.9 \pm 0.1 pb)$$

- Observed significance 7.9σ (5.9 expected) $\to$ http://arxiv.org/abs/1112.0536v1
- Fit WW and WZ also separately.
- See talk by Yuji Enari tomorrow for b-tagged analysis

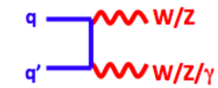


Conclusion



- EWK physics a rich and interesting place
  - SM tests
  - Higgs benchmark
  - New physics searches
- Huge work over ten years of Run 2
- **Allows for measuring very small cross sections**
- **Setting some of the tightest limits on anomalous TGCs**
- **Some measurements are unique at the Tevatron and some other are complementary to the LHC**

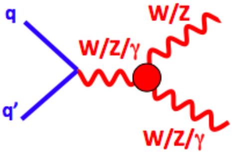
Backup slides



Dibosons

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu)\right.$$

$$\left. + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$



$$\mathcal{L} = -\frac{e}{M_Z^2}\left[f_4^V(\delta_\mu V^{\mu\beta})Z_\alpha(\delta^\alpha Z_\beta) + f_5^V(\delta^\sigma V_{\sigma\mu})Z^{\mu\beta}Z_\beta\right]$$

EM gauge invariance and C and P conservation
→ 5 independent TGCs for WW $\{g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z, \lambda_\gamma\}$

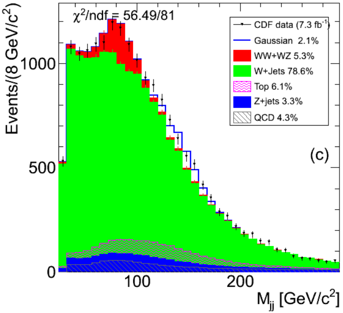
Wγ sensitive to κ_γ, λ_γ
WZ sensitive to g_1^Z, κ_Z, λ_Z

Standard Model: $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ so consider Δg_1^Z, $\Delta\kappa_Z$
$\lambda_Z = \lambda_\gamma = 0$

$$\Delta a(\hat{s}) = \frac{\Delta a_0}{(1+\hat{s}/\Lambda_{NP}^2)^n}$$

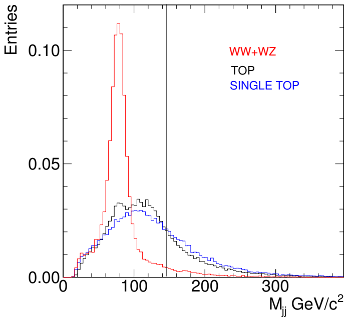
ZγZ vertex: Zγ sensitive to $h_3^Z, h_3^\gamma, h_4^Z, h_4^\gamma$
ZZγ vertex: ZZ sensitive to $f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma$ all zero in SM

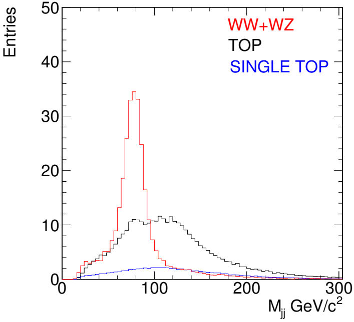
Wjj anomaly: JES



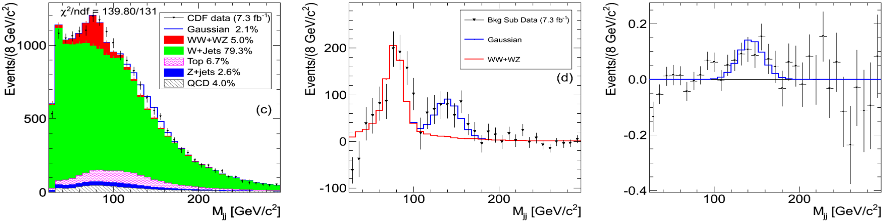
Wjj anomaly: accounting for $t\bar{t}$

- don't see it enhanced with b-tags
- Top does not peak at 150 after the detector simulation
- If we artificially double the single top cross section $\rightarrow$ negligible effect
- Left plot: templates normalized to area. Right plot: template normalized to their expectation



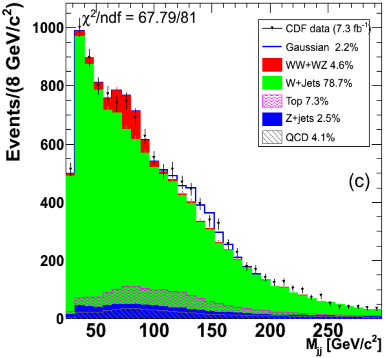


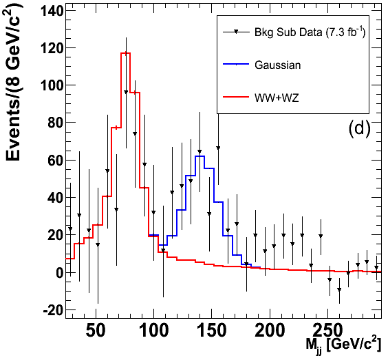
Wjj anomaly: SHERPA



Wjj anomaly: Harder cuts

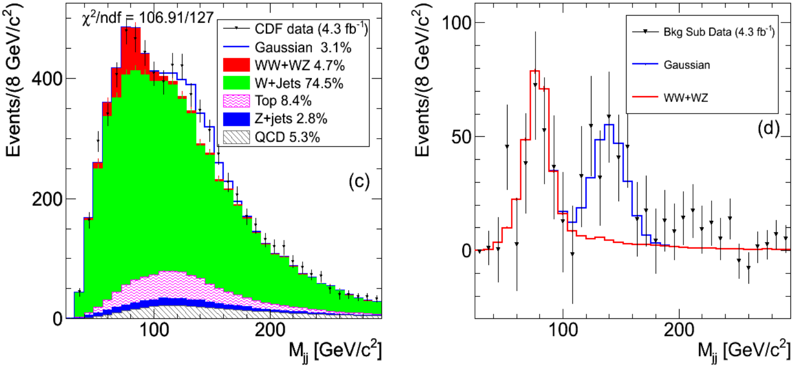
- $p_T(Wlep) > 60$





Wjj anomaly: Harder cuts

- $p_T(Wlep) > 60$ and $\delta\phi > 1$



D0 Wjj study

- Fit dijet mass distributions for all SM processes to the data
  - Construct a χ^2 function from the ratio of Poisson likelihoods and include prior information on the systematic uncertainties

$$\chi^2(\theta, S, B; D) = 2\sum_{i=0}^{N_{bins}} (B_i + S_i - D_i) - D_i \ln\left(\frac{B_i + S_i}{D_i}\right) + \sum_{k=0}^{N_{syst}} \theta_k^2$$

D = observed number of events
$S(\theta_k)$ = predicted number of signal events
$B(\theta_k)$ = predicted number of background events
θ_k = number of standard deviations systematic k has been pulled away from nominal

- Templates can vary within systematic uncertainties, constrained by Gaussian priors
- Can "float" a parameter by removing the θ^2 prior constraint
  - Float cross sections for Diboson and W+jets contributions

D0 Wjj study

Source of systematic uncertainty	Diboson signal	W+jets	Z+jets	Top	Multijet	Nature
Trigger/Lepton ID efficiency	±5	±5	±5	±5		N
Trigger correction, muon channel	±5	±5	±5	±5		D
Jet identification	±1	±1	±2	±1		D
Jet energy scale	±10	±5	±7	±5		D
Jet energy resolution	±6	±1	±3	±6		D
Jet vertex confirmation	±3	±3	±4	±1		D
Luminosity	±6.1	±6.1	±6.1	±6.1		N
Cross section		±6.3	±6.3	±10		N
V+hf cross section		±20	±20			N
V+2 jets/V+3 jets cross section		±10	±10			N
Multijet normalization					±20	N
Multijet shape, electron channel					±1	D
Multijet shape, muon channel					±10	D
Diboson modeling	±8					D
Parton distribution function	±1	±5	±4	±3		D
Unclustered Energy correction	$\pm<1$	±3	±3	$\pm<1$		D
ALPGEN η and $\Delta R(jet1, jet2)$ corrections		$\pm<1$	$\pm<1$			D
ALPGEN W p_T correction		$\pm<1$				D
ALPGEN correction Diboson bias	±1	±1	±1	±1		D
Renormalization and factorization scales		±1	±1			D
ALPGEN parton-jet matching parameters		±1	±1			D
Parton shower and Underlying Event		±2	±2			D